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Fast Timing of Air Shower Fronts

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Abstract

In order to design a telescope for use in ultra-high energy γ-ray astronomy one needs to carefully consider those effects which determine the system angular resolution. This paper considers detector and discriminator designs for such a system including a consideration of the effect of the spread of particles in the shower front. An angular resolution of $\sim 1°$ at energies of 10^{15} eV can be achieved.

1. Introduction

With the recent discovery of ultra-high energy (UHE) γ-ray sources, by means of cosmic ray shower arrays (Samorski and Stamm 1983; Lloyd-Evans *et al.* 1983; Protheroe *et al.* 1984; Protheroe and Clay 1985), has come renewed interest in the problem of designing air shower arrays with the best possible angular resolution (Linsley 1985). Point sources of UHE γ rays are observed against a background of conventional particle cosmic rays and the detection threshold for a source depends critically on the number of background events detected within the array angular uncertainty about the source (Protheroe 1984). A decrease in angular uncertainty by a factor of 2 (from the 2° to 3° typical of present generation arrays) would decrease this background by a factor of 4 thus making a dramatic improvement to the chances of observing new sources.

Cosmic ray showers with energies of $\sim 10^{15}$ eV are usually detected by using ground based arrays of particle detectors (usually consisting of plastic scintillators with areas of ~ 1 m^2). The arrival direction of a shower is determined by measuring the relative arrival times of the shower front (which is almost planar and perpendicular to the direction of propagation of the shower) at a number of these detectors and assuming that the front travels at the speed of light. This fast timing technique depends on accurate registrations of the times of arrival at the various detectors and the resulting angular uncertainty is given by the timing uncertainty divided by the baseline (divided by c). Thus, a typical timing uncertainty of a few ns over a baseline of 20 m will give a few degrees angular uncertainty. The shower front itself is not quite planar, typically having a radius of curvature of the order of 1 km so that, in order to retain angular accuracy with a relatively simple array, one would prefer to use a baseline

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not much greater than a few tens of metres. One reaches a similar conclusion when one considers the steepness of the lateral distribution of particle density from the core. This distribution has a typical sea level scale of approximately tens of metres (the Molière radius is ~ 80 m) and, to define the shower front by observing particles with detectors of a practical size, one would not wish to go to large core distances.

Here we examine the problems involved in constructing a fast timing system with an angular uncertainty of $\lesssim 1°$. Since we felt that the arguments above influenced us to limit the baseline to ~ 20 m, this involves building detectors which have timing uniformity over their sensitive area of better than 1 ns and timing discriminators which will signal the arrival of the first detected particle with an uncertainty of $\lesssim 1$ ns. One needs also to be confident that particles sampled in the shower front can be detected within 1 ns of the 'true' front.

2. Detector

We have examined a standard cosmic ray scintillation detector from the point of view of its use in a fast timing system. Conventional detectors of area $\sim 1\ \mathrm{m}^2$ in a pyramidal enclosure have been discussed by Clay and Gregory (1978). Light from the scintillator slab is reflected internally within the detector enclosure until it is finally absorbed in the photomultiplier face. Such a detector is painted internally with highly reflective paint and may include a light baffle to prevent some direct light reaching the photomultiplier in order to achieve good uniformity of light collection (Clay and Gregory 1978). A fast timing system may not be compatible with such a design since one would not want to deliberately slow the collection of light with the use of a baffle, although one would still want to obtain acceptable uniformity of light collection. With a sensitive photomultiplier and a scintillator with a good output level, one can obtain improved uniformity of a non-baffled system by moving the tube further from the scintillator (Clay and Gregory 1978). There may also be some advantages in eliminating internal reflections in the detector provided that one does not need to have optimally efficient total light collection. The latter point is debatable and, to an extent, a matter of taste since the first light which is used for fast timing will arrive at the photomultiplier directly with or without internal reflection of later light.

We have studied the uniformity in time of light collection from a white pyramidal detector of area 1 m^2 and height 30 cm and also from non-reflecting detectors with the photomultiplier at 30, 60 and 90 cm from the scintillator. The general arrangement is shown in Fig. 1*a*. Single particles were selected with a small (40 mm) diameter fast scintillation detector (~ 4 ns risetime) and a trigger pulse sent to a fast transient recorder (Clay and Wild 1985) operating at 2 ns per sample. The recorder then recorded pulses from the large detector under test and averaged 10^3 pulses for each of five representative positions (Fig. 1*b*) on the 1 m^2 area. The resulting time distributions are shown in Fig. 2. It is noteworthy that, as expected, whilst the signals from the white detector (*a*) are of greater amplitude, they are also appreciably longer. Also, the time difference between observation of the peak of the pulse from central areas of the detector compared with observation of the peak from corners of the detector is least for large separations of photomultiplier and scintillator. Indeed, the differences in peak positions over the scintillator correspond well to the differences in the geometric delays of the various light paths. In this respect, the 90 cm separation (*d*) is clearly the best with almost no change ($\lesssim 1$ ns) in the time of the pulse peak. We

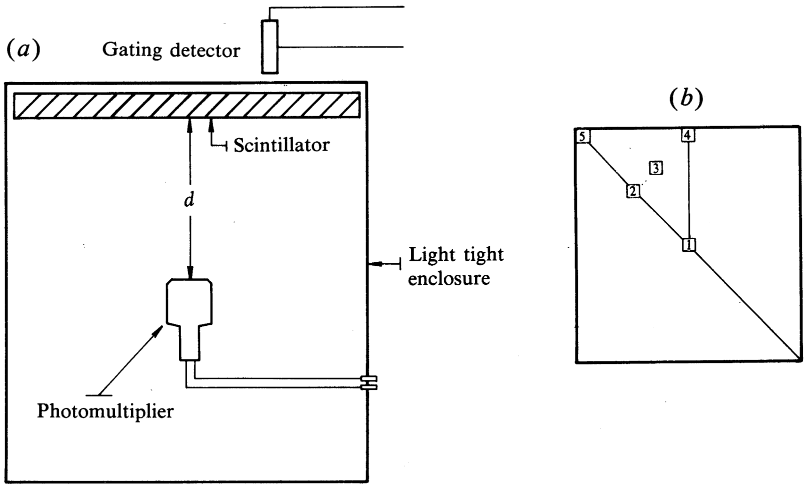

Fig. 1. Diagrams of (*a*) the detector arrangement and (*b*) the plan view of the detector indicating the five representative positions.

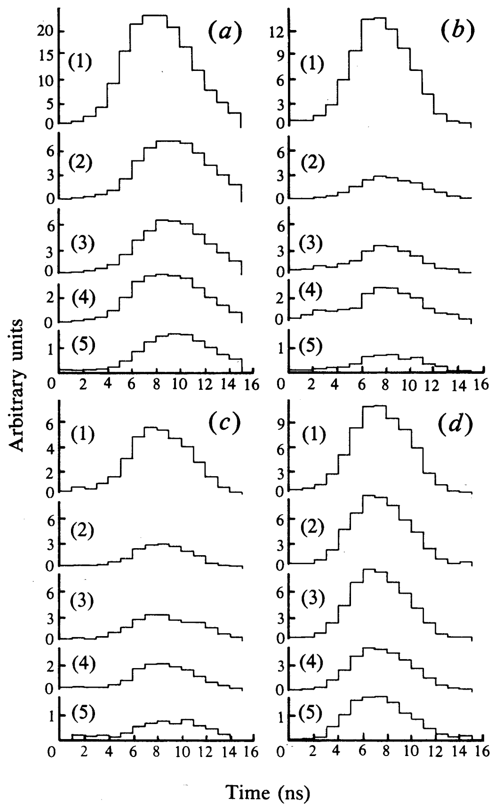

Fig. 2. Resulting time distributions for each of the five representative positions of Fig. 1*b* for (*a*) white interior, $d = 30$ cm, (*b*) black interior, $d = 30$ cm, (*c*) black interior, $d = 60$ cm, and (*d*) black interior, $d = 90$ cm. Note that the gain was increased for the 90 cm spacing in (*d*).

note that since the tube gain was increased for the 90 cm studies, one cannot directly compare the absolute times between all four studies but relative times within studies will be correct. The relative times of the peaks for the 90 cm detector were carefully checked with a somewhat faster gating detector (a Philips XP2040 photomultiplier viewing a 50 mm scintillator attached to the centre of its faceplate so as to give the fastest possible response) and a reduced time sample interval. A total time spread of $\sim 0 \cdot 3$ ns was found between the various positions on the detector. A 90 cm spacing detector painted black internally was adopted as an acceptable design.

3. Discriminator

The heart of a fast timing system is the discriminator which produces an output pulse when an input pulse exceeds a predetermined amplitude. In practice the output is delayed by a fixed time although this is routinely calibrated out in practical arrays. The photomultiplier will have a finite risetime and the air shower particles will not arrive as an impulse but will be spread through the shower front. As a result, a conventional discriminator will have time jitter depending on whether it triggers near the base or near the peak of the rising pulse. With our photomultiplier tube this jitter is of a few ns. This is unacceptable for our 1 ns system and we have investigated three possible improved systems, the constant fraction discriminator, the transient recorder, and what we will call the double discriminator.

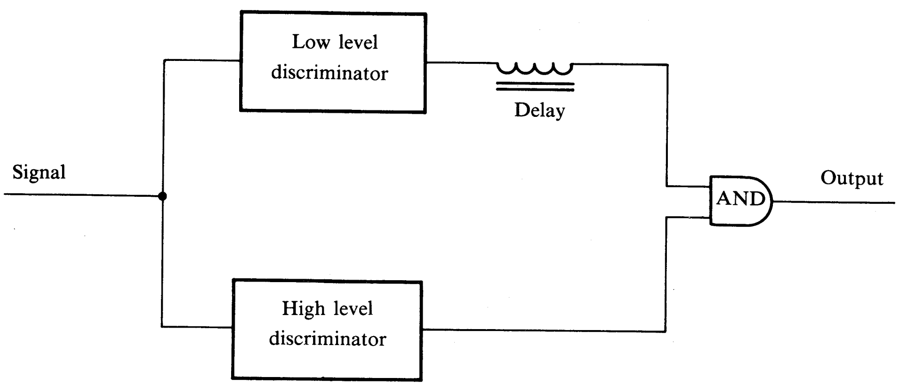

Fig. 3. Diagrammatic representation of the 'double discriminator'.

The constant fraction discriminator (see e.g. Paulus 1985) is common for fast timing in high energy physics. It triggers at a predetermined point on the pulse rise in terms of the total pulse amplitude. Time jitter can be essentially zero for pulses of fixed shape. Unfortunately, in an air shower we deal with a number of particles being detected over a time spread which varies from shower to shower. In this case, the rise time is not fixed and the constant fraction discriminator will have jitter (but will still be better than a conventional discriminator). We investigated the possibility of putting a fast ($\lesssim 1$ ns per sample) transient recorder on a conventionally discriminated detector and using a microprocessor to extrapolate back to the time of zero signal, the start of the first particle signal in the pulse. This technique worked well but with testing it became clear that there was a much simpler alternative with almost the same timing accuracy, the 'double discriminator' (see Fig. 3).

In the leading edge of the shower front at relatively small core distances, one expects to find mainly high energy particles, each of which will produce a signal like a 'vertical equivalent muon', the standard calibration signal. If a discriminator is set well below this single particle level, it will always trigger close to the start of the first signal in the shower front. Such a simple discriminator is impractical since it will trigger at very high rates and the array will trigger on many accidental coincidences. We therefore put the detector output also to a second discriminator at a much higher ($\gtrsim 10$ times) level, in fact at a conventional level for an air shower array (a few particles). A logical AND is taken between the two discriminator outputs so that the timing output (slightly delayed by a known amount) retains the time accuracy of the low level discriminator and also has the slow rate of the high level discriminator. We have used such a discriminator to trigger our transient recorder (at 1 ns per sample), and have directly observed the jitter of the discriminator output relative to the start of the first air shower signal for typical shower signals containing $\gtrsim 6$ particles. The standard deviation of the double discriminator jitter was 0·51 ns, of a constant fraction discriminator set at 50% amplitude it was 0·73 ns and of a constant amplitude discriminator triggering near the peak it was 1·62 ns. It appears that either a constant fraction discriminator set at or below half height or a double discriminator will give a timing accuracy better than 1 ns.

4. Detector Area

The detector area affects fast timing in two ways. As one detects events away from the zenith, the shower front takes a finite time to cross the detector area and causes a time variation of approximately $d \sin \theta / 2c$, d being the detector diameter and θ the shower zenith angle. Also, as the area decreases, less particles are detected and the chance of detecting a particle in the first ns of the shower front is reduced. A compromise must therefore be reached.

If one observes showers at large zenith angles θ, the array baseline becomes foreshortened by $\cos \theta$, and the detectors elongated by $\sin \theta$ (the shower front taking longer to cross the detector area), so that eventually the physical size of the detector will limit the array angular resolution. With a baseline of 20 m and a detector diameter of 1 m the angular resolution from this effect will be approximately $\sin \theta / 40 \cos \theta$ rad, or 1° for a zenith angle $\sim 30°$. This is the angle at which atmospheric attenuation begins to severely limit scintillator arrays and so might be acceptable since, above this, only appreciably higher energy showers are preferentially detected by the much less efficient system. However, one would not wish to increase much above 1 m diameter for the detectors or decrease below 20 m for the baseline.

The longitudinal thickness of the shower front on axis is not known except to say that it is below ~ 10 ns. We triggered our fast detector at about the 10 particle level and observed many disc thicknesses. Such a trigger will preferentially detect showers within ~ 20 m of the core so that our thicknesses will indicate the thicknesses at typical core distances of interest to us. We found a mean disc thickness at half maximum of 9·6($\pm$0·13) ns compared with a single particle impulse response of 7·2($\pm$0·3) ns so that the true width will be between approximately 3 and 6 ns depending on whether one uses the limits of signal and system response combined linearly or in quadrature. (A similar result was obtained by triggering on ~ 20 particles.) In this case, in order to reasonably guarantee that a leading sampled particle is within 1 ns of the 'true' shower front, one would need a particle density of $\gtrsim 6$ m^{-2}.

It would appear that the detector would need an area of $\sim 1\ \mathrm{m}^2$ to detect showers of a useful size and, if such a detector were to detect showers with a system baseline of ~ 20 m and if a particle threshold density were set at $\sim 6\ \mathrm{m}^{-2}$, the array would have a size threshold a little below 10^5 particles providing that the observed showers had lateral distributions which were not too flat (shower age, $s \lesssim 1 \cdot 6$).

5. Conclusions

We have built a prototype detector/discriminator system which can be used as a basis for an ultra high energy γ-ray telescope with an angular resolution of $\sim 1°$ and a shower size threshold of $\sim 10^5$ particles (primary energy $\sim 10^{15}$ eV). Nanosecond timing accuracy can be achieved with careful detector design and the use of a suitable discriminator.

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